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# DEVELOPMENT OF AN IMPULSE SOURCE-BASED WAVE-CURRENT INTERACTION MODEL

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**Abstract.** The analysis of wave-current interaction (WCI) in numerical wave tanks (NWTs) requires the simultaneous generation of a current velocity profile and free surface waves. This paper presents a novel approach to simulate the WCI using an impulse source-based methodology together with a numerical beach implementation. Three additional terms are added to the momentum equation, to incorporate current and wave generation as well as the numerical beach. The model components, i.e. wave- and current generation and WCI are verified independently against two sets of reference data [1, 2]. The results show excellent agreement for the wave-only case, while for the current-only and thus WCI, some model weaknesses can be identified.

## 1 INTRODUCTION

The interaction between waves and currents is a common problem in the ocean and marine engineering sector. A first description of wave-current interaction (WCI) was delivered by [3]. Since then, numerous studies have been performed using different analysis tools ranging from analytical descriptions to experimental tank testing and numerical models. The main analysis tool used to date is scaled experimental tank tests [4, 5, 6, 7, 8]. Such tests are prone to scaling effects, undesired influences of measurement equipment and test environment, and significant costs. In times of increasing computational power, CFD-based numerical wave tanks (CNWT) are a viable alternative to experimental tank tests, avoiding the aforementioned problems. However few CNWTs models able to simulate WCI have been described in literature [9]-[13].

This study presents an impulse source-based WCI model for CNWTs. Waves and currents are simultaneously generated through the inclusion of source terms, added to the Reynolds Averaged Navier-Stokes (RANS) equations. The wave generation is based on

the implementation presented in [14]. The constant current is generated and controlled through another impulse correction term.

Results are presented for wave-only, current-only and WCI simulations. For verification purposes, the results will be compared to literature benchmark cases [1] and [2].

The remainder of the paper is organised as follows. Section 2 describes the implementation of the additional source terms in the impulse equation and the setup of the numerical wave-current tank is explained. Following, the case study used as benchmark for the verification is described in Section 3. The results of this verification study are presented and discussed in Section 4. Finally, conclusions are drawn in Section 5.

## 2 INTERNAL WAVE AND CURRENT GENERATION

A RANS model includes the following impulse equation:

$$\frac{\partial(\rho\mathbf{U})}{\partial t} + \nabla \cdot (\rho\mathbf{U}\mathbf{U}) = -\nabla p + \nabla \cdot \mathbf{T} + \rho\mathbf{F}_b \quad (1)$$

where  $t$  is time,  $\mathbf{U}$  the fluid velocity,  $p$  the fluid pressure,  $\rho$  the fluid density,  $\mathbf{F}_b$  the external forces such as gravity, and the viscous stress tensor  $\mathbf{T} = \mu\nabla^2\mathbf{U} + \frac{1}{3}\nabla(\nabla \cdot \mathbf{U})$ , with the dynamic viscosity  $\mu$ . To implement the impulse sources for wave and current generation, as well as a numerical beach for wave absorption, three terms are added to Eq. (1):

- $r_w\rho\mathbf{a}_{wm}$  : This is the source term used for wave generation, where  $r_w$  is a binary scalar variable that defines the wavemaker region and  $\mathbf{a}_{wm}$  is the acceleration input to the wavemaker at each cell centre within  $r_w = 1$ . This term is based on the implementation of an internal wavemaker in [14].
- $r_c\rho\frac{\mathbf{U}_t - \mathbf{U}}{\Delta t}$  : This is the source term used for current generation, where  $r_c$  is a binary scalar variable that defines the current generation region. At each cell centre within  $r_c = 1$ , the acceleration input is defined through the difference between the velocity field  $\mathbf{U}$  and a target velocity field  $\mathbf{U}_t$ .
- $s\vec{n}_z\rho\mathbf{U}$  : This describes a dissipation term used to implement a numerical beach, where the variable  $s$ , with unit  $[\text{s}^{-1}]$ , controls the strength of the dissipation [15]. Compared to the implementation in [14] and [15], herein, the beach only acts in vertical, z-direction, to dissipate the waves while allowing for a steady current flow in x-direction.

Introducing these three terms to Eq. (1), yields the adapted impulse equation:

$$\frac{\partial(\rho\mathbf{U})}{\partial t} + \nabla \cdot (\rho\mathbf{U}\mathbf{U}) = -\nabla p + \nabla \cdot \mathbf{T} + \rho\mathbf{F}_b + r_w\rho\mathbf{a}_{wm} + r_c\rho\frac{\mathbf{U}_t - \mathbf{U}}{\Delta t} + s\vec{n}_z\rho\mathbf{U} \quad (2)$$

## 2.1 Numerical wave and current tank

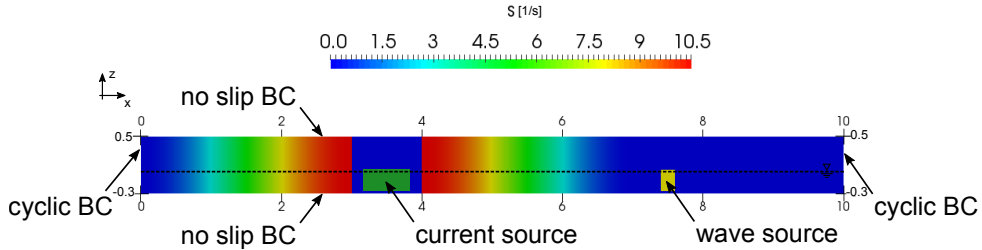
To generate a superimposed wave and current field, two separate source regions for the wave and current generation have to be defined. Furthermore, to ensure a constant current-velocity profile along the water column and since the instantaneous velocity field in the current source region is used to correct the impulse input, the numerical beaches have to embrace the current source. A schematic of the tank layout, position of the different source regions and the numerical beach is depicted in Figure 1.

For the numerical beach, the dissipation strength is gradually increased over the beach length  $\ell$ , following Eq. (3).

$$s(x) = -2 \cdot s_{max} \left( \frac{(\ell - x)}{\ell} \right)^3 + 3 \cdot s_{max} \left( \frac{(\ell - x)}{\ell} \right)^2 \quad (3)$$

While the current source strength is internally adapted during the simulation based on the difference between the desired and instantaneous current velocity, the input for the wave source is defined a priori, requiring preliminary calibration runs [14].

To enable a constant current flow in the domain, cyclic boundary conditions (BCs) are used at the inflow and outflow boundaries of the numerical domain. For the top and bottom boundaries of the domain, no slip wall boundaries are used. To reduce the required time for the flow development, the whole domain is initialised with the desired horizontal velocity field. In this initial study of the WCI using impulse sources, all simulations are performed in a pseudo two-dimensional domain, i.e. one cell thickness. A minimum cell size of 10 cells per wave height with a maximum aspect ratio of 2 and 4 is set in the free surface region and in vicinity of the bottom wall, respectively.



**Figure 1:** Positioning of the numerical beach, the current and wave source in the numerical wave-current tank

## 3 CASE STUDIES

For verification purposes of wave-only and WCI simulations, the present numerical setup will be used to perform simulations based upon the numerical study by Zhang et al. [2]. A uniform, constant current of  $U_t = 0.08 \text{ m s}^{-1}$  acts in combination with waves of period  $T = 1 \text{ s}$  and heights  $H = \{0.010 \text{ m}, 0.023 \text{ m}, 0.0361 \text{ m}\}$ . The water depth is set to  $d = 0.3 \text{ m}$ , yielding a wave length  $\lambda = 1.372 \text{ m}$  according to the linear dispersion relation.

A  $k - \epsilon$  turbulence model is used through the study.

Free surface elevation data and velocity profiles along the water column are compared against experimental data from [16] for wave-only and WCI cases. These data will be used in the present study, to verify the numerical setup.

Unfortunately, [2] does not provide data for the current-only case. Hence, for verification purposes of current-only simulations, the present numerical setup will be used to perform simulations based upon the numerical study by Teles et al. [1].

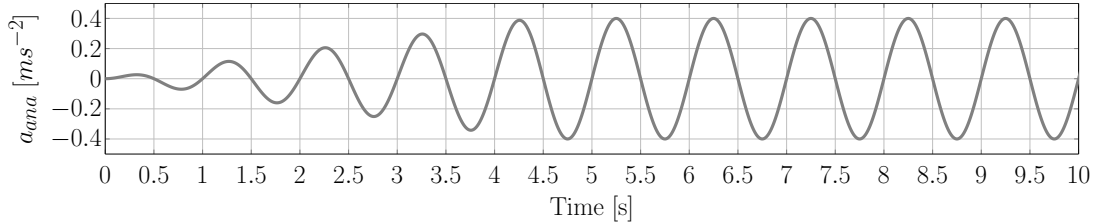
Using the *Code-Saturne* CFD solver, this study investigates the effect of different turbulence models, i.e.  $k - \epsilon$ ,  $k - \omega$ SST and the Reynolds Stress Model (RSM). Numerical results are generated for two different reference cases: [17] and [18].

The presented numerical and experimental data for the latter reference case will be used for the verification. A uniform, constant discharge of  $80\text{L s}^{-1}$  ( $= U_t = 0.16\text{m s}^{-1}$ ) in a  $0.5\text{m}$  deep tank is simulated.

## 4 RESULTS AND DISCUSSION

### 4.1 Preliminary studies

In a preliminary study, the input for the wave impulse source will be determined through linear-scaling calibration. A time trace snippet for  $a_{ana}$ , where  $\mathbf{a}_{wm} = [a_{ana} \ 0 \ 0]^T$ , is shown in Figure 2. The source length and height, as well as the position are based upon the parameters presented in [14], i.e. source height  $d$ , source length  $0.15\lambda$  and the source centre is position  $1/3 d$  below the still water level.



**Figure 2:** Source input  $a_{ana}$  for wave generator

Furthermore, the maximum beach strength  $s_{max}$  and beach length  $\ell$  are determined through parameter studies, with the goal of minimising/eliminating wave reflection. Guidance for the selection of  $s_{max}$  and  $\ell$  can be found in [14] and [19]. Ultimately,  $s_{max}$  is set to  $10.5\text{s}^{-1}$  and  $\ell \approx 2\lambda$ .

For the current source, a parameter study on the source region dimensions has been performed. The final dimensions are  $0.8\text{m} \times 0.325\text{m}$ , for the source length and height. The centre of the current source region is placed at  $0.42d$  below the free surface. To avoid undesired acceleration of the air phase, the current source only marginally pierces the still water line. To prevent violation of the no-slip condition and potential divergence in the turbulence model, a gap between the bottom boundary and current source region of  $0.013\text{m}$  is kept.

## 4.2 Wave-only

First, results for the wave-only case are compared to the numerical and experimental data presented in [2].

The impulse source wavemaker has already been validated against wave theory in [14, 20]. In this study, the simulation results are compared to experimental and numerical reference data. Figure 3 shows the free surface elevation, averaged over 15 consecutive periods ( $40s \leq \text{Time} \leq 55s$ ) at two different locations: a) at the centre position of the current source, i.e. 3.5m; b) at a position downstream of the current and wave source, i.e. 9.5m.

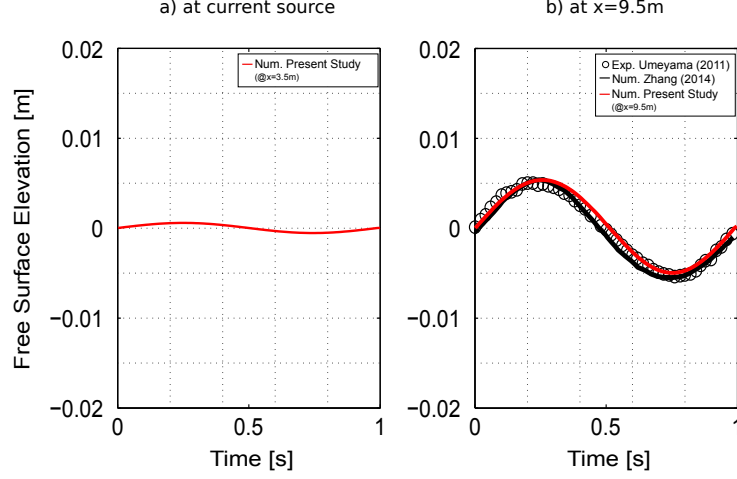
At the centre location of the current source, zero surface elevation is desired, so that the input impulse term is not biased by parasitic wave elevation. As shown in Figure 3 a), this is successfully achieved. At the evaluation location, i.e.  $x = 9.5\text{m}$ , the wave field should accurately recreate the desired wave field. As shown in Figure 3 b), the numerical results from the present study match very well with both the experimental and numerical reference data.

Figure 4 a)-c) show the horizontal, x-velocity, measured along the water column, again at the two different locations  $x = 3.5\text{m}$  (Figure 4 a)) and  $x = 9.5\text{m}$  (Figure 4 b) and c)). Furthermore, at the evaluation location, velocities are measured for time instances showing a wave crest (b)) and a wave trough (c)). The results are the averaged velocities over 15 consecutive crests/troughs.

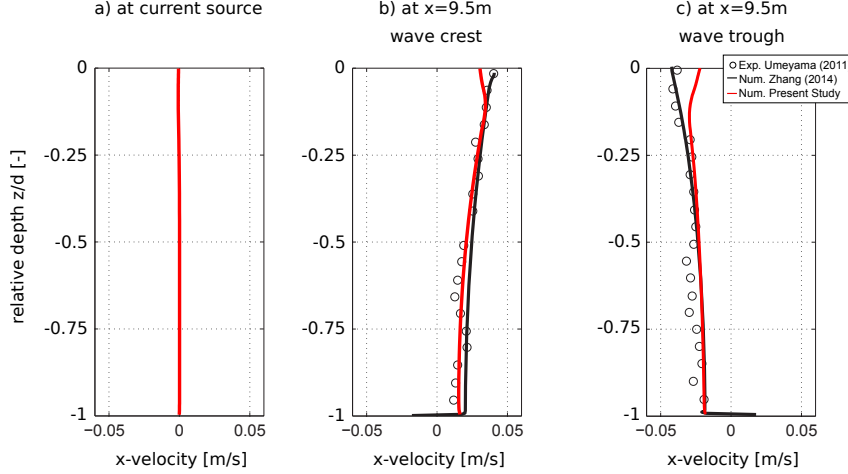
As for the surface elevation, the horizontal velocity component at the centre location of the current source should be zero throughout the simulation. Figure 4 a) shows, that this has been achieved.

At the evaluation location, the horizontal velocities, both at wave crests and troughs, should recreate the desired velocity field. At the wave crest, Figure 4 b) shows very good agreement between the experimental data and the numerical reference. As for the surface elevation, in general the impulse source wavemaker is able to recreate the desired velocity field more accurately than the methodology employed in the reference study. However, considerably larger deviations can be observed close to the free surface.

At the wave trough, results from the present study coincide with the numerical reference for  $0.25 \leq z/d \leq 1$ . Compared to the experimental data, both numerical models show noticeable differences for  $0.5 \leq z/d \leq 0.75$ . However, since both numerical models are able to recreate the velocity field at the wave crest and coincide in the aforementioned region, it can be assumed that inaccuracies in the experimental measurements lead to the mismatch between the data sets. As for the wave crest, larger deviations between experimental and numerical reference data can be observed closer to the free surface, i.e.  $0 \leq z/d \leq 0.2$ .



**Figure 3:** Free surface elevation for the wave only tests case, comparing experimental data (o) [16], numerical data by Zhang et al. [2] and numerical results from the present study



**Figure 4:** Horizontal x-velocities for the wave only tests case, comparing experimental data (o) [16], numerical data by Zhang et al. [2] and numerical results from the present study

### 4.3 Current-only

To test the capability of the proposed method to generate a steady current stream, current-only simulations are performed. Since the reference case in [2] does not provide data for current-only cases, results from [1] as used to verify the functionality of the current generator. For these cases, the wave source has been disabled, while the vertically acting beach is still in place. At the beginning of the simulation, a horizontal velocity of  $0.15\text{m/s}$  is initialised in the whole numerical domain.

The horizontal velocities at the evaluation point  $x = 9.5\text{m}$  at different time instances  $10\text{s} \leq t \leq 100\text{s}$  are shown in Figure 5.

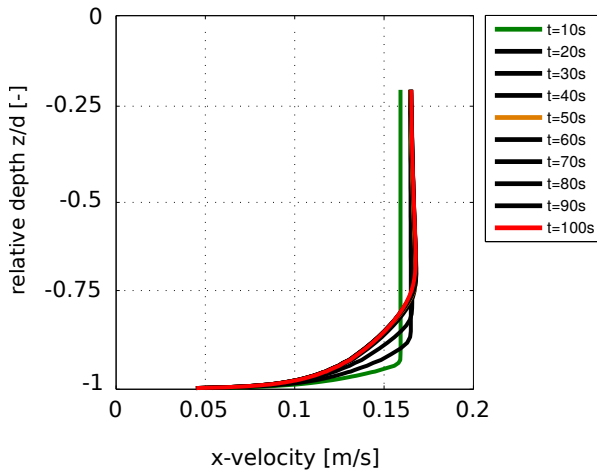
The results show, that a steady state current flow is only established after  $40\text{s}$ . Furthermore, over time, the wall boundary layer on the tank floor increases. At time instances

$t > 40s$ , the x-velocity increases in the region  $-1 \leq z/d \leq -0.75$ , after which it remains constant at a velocity of  $\approx 0.165m/s$ . This maximum steady state velocity is slightly higher than the desired target velocity  $0.16m/s$ .

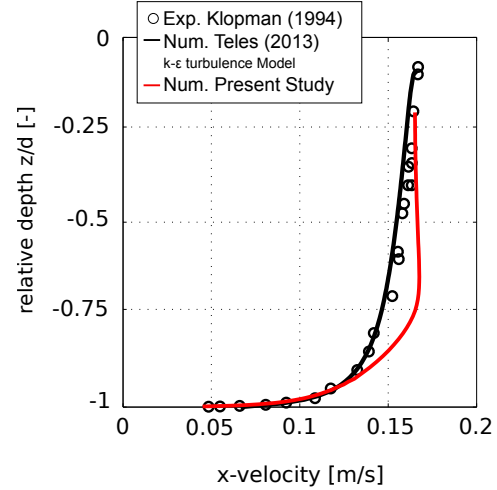
In Figure 6 again shows the horizontal x-velocity profile generated with the proposed impulse current generator at the evaluation location at time  $t = 100$ . Additionally, the plot contains numerical and experimental data [1, 18].

Comparing the results from the present study to both, the experimental and numerical reference, a good agreement close to the bottom boundary ( $-1 < z/d < -0.85$ ) can be observed. Also, towards the free surface ( $-0.35 < z/d < 0$ ), reasonable match is found. However, for ( $-0.85 < z/d < -0.35$ ) relatively large deviations between the results from the present study and the reference data can be observed.

At the time of writing, the source for this mismatch is unknown. It is assumed, that the use of wall-functions in the employed implementation of the  $k - \epsilon$  turbulence model may affect the numerical results. Also, no error bars on the experimental results are provided, so that the influence of the measurement uncertainty cannot be taken into account, when analysing the fit between the numerical and experimental reference data.



**Figure 5:** Current-only test case based on [1]: Horizontal x-velocities at the evaluation location  $x = 9.5m$  at different time instances  $10s \leq t \leq 100s$



**Figure 6:** Horizontal x-velocities at the evaluation location  $x = 9.5m$  at  $t = 100s$ : Comparing experimental data (o) [18], numerical data by Teles et al. [1] and numerical results from the present study

#### 4.4 Wave-current interaction

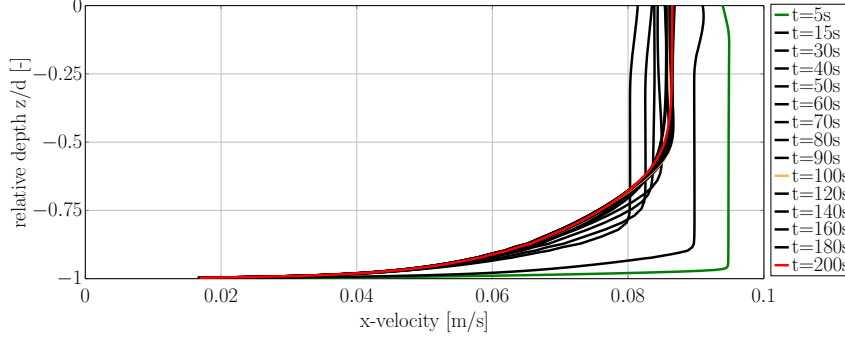
As shown in Figure 5, transient behaviour of the current velocity profile can be observed. To neglect any influence from this flow development, a current-only case is simulated for the reference case in [2].

For these cases, the wave source has been disabled, while the vertically acting beach is still in place. At the beginning of the simulation, a horizontal velocity of  $0.06m/s$  is initialised in the whole numerical domain.



The horizontal velocities at the evaluation point  $x = 9.5\text{m}$  at different time instances  $5\text{s} \leq t \leq 200\text{s}$  are shown in Figure 7.

The results reveal, that a steady state current flow is only established after  $100\text{s}$ . At time instances  $t > 100\text{s}$ , the x-velocity increases in the region  $-1 \leq z/d \leq -0.75$ , after which it remains constant at a velocity of  $\approx 0.086\text{m/s}$ .



**Figure 7:** Current-only tests case as in [2]: Horizontal x-velocities at the evaluation location  $x = 9.5\text{m}$  at different time instances  $5\text{s} \leq t \leq 200\text{s}$

This transient behaviour of the current velocity profile has to be taken into account when analysing the results of the WCI case. Hence, for the verification of the WCI, surface elevation data are averaged over 20 consecutive periods between  $100\text{s} \leq \text{Time} \leq 120\text{s}$ .

Results for the free surface elevation and velocity profile are shown in Figure 8 and 9, respectively. Figure 8 a) includes the experimental data from [16], numerical data from [2] and numerical results from the present study. Figure 8 b) and c) show the difference between the wave-only and WCI case for the present study and the reference numerical results, respectively.

Compared to the experimental data, the presented implementation of the WCI methodology shows a relatively good fit and the start and end of each period. Between  $0.25\text{s} \leq \text{Time} \leq 0.75\text{s}$ , larger deviations can be observed. The numerical data under-predict the measured surface elevation.

Comparing the numerical data from the wave-only and WCI case gained from the present model, a decrease in the amplitude of the wave can be observed. Also the phase is influenced by the current, shifting the trough of the wave. Comparing data from the wave-only and WCI case for the numerical reference case, the decrease in wave amplitude and the phase shift can also be observed, however to a larger extend.

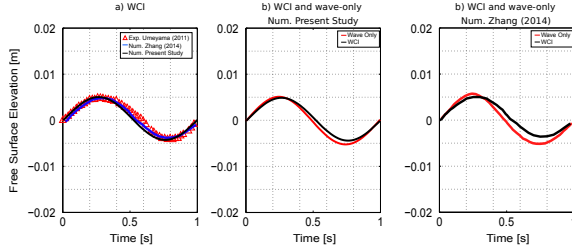
Figure 9 shows the horizontal x-velocity at the evaluation location ( $x = 9.5\text{m}$ ) for the wave crest (Figure 9 a)) and trough (Figure 9 b)). As for the wave only case, numerical results from the present model are compared to experimental and numerical reference data.

Overall, a relatively small deviations between the present numerical data and the reference data can be observed. The numerical reference shows good agreement with the experimental data for the wave crest in a the region  $-0.5 \leq z/d \leq 0$ . This good match can also be observed for the present implementation. Towards the bottom boundary, in

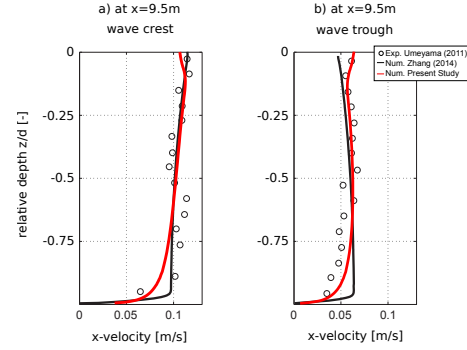
the region  $-0.9 \leq z/d \leq -0.75$ , larger deviations between the reference data (numerical and experimental) and the present study can be seen.

For the wave trough, the present implementation, again, shows good agreement with the experimental and numerical reference data at the top of the water column,  $-0.5 \leq z/d \leq 0$ . It is noteworthy that the behaviour close to the free surface ( $-0.1 \leq z/d \leq 0$ ) is captured very well using the present implementation. Towards the bottom boundary, the current implementation shows deviations to the experimental data, however, provide a better fit than the numerical reference.

In the light of the current-only verification case, the deviations close to the bottom boundary are expected and further analysis is required to determine the source of the error.



**Figure 8:** Free surface elevation for the WCI tests case, comparing experimental data ( $\Delta$ ) [16], numerical data by Zhang et al. [2] and numerical results from the present study



**Figure 9:** Horizontal x-velocities for the wave only tests case, comparing experimental data (o) [16], numerical data by Zhang et al. [2] and numerical results from the present study

## 5 CONCLUSION

To simultaneously generate waves and currents in a numerical wave tank, a impulse source based approach has been presented. From the verification study, using numerical and experimental reference data, the following conclusion can be drawn:

- The impulse source wavemaker is able to accurately create the desired wave field
- The tank layout effectively shields the current generation area from wave action
- Generated current passes the numerical beaches
- Further work is required to recreate flow profiles accurately, especially close to the bottom boundary
- Despite some remaining issues with current generation the tendency of decreasing wave height and phase shift for waves travelling in current direction is captured correctly and the presented method is a promising tool to simulate WCI.

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